

# Science with Generation-X

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## ABSTRACT

We report on the prospects for the study of the first stars, galaxies and black holes with the Generation-X Mission. Generation-X is a NASA "Vision Mission" which completed preliminary study in late 2006. Generation-X was approved in February 2008 as an Astrophysics Strategic Mission Concept Study (ASMCS) and is baselined as an X-ray observatory with 50 square meters of collecting area at 1 keV (500 times larger than Chandra) and 0.1 arcsecond angular resolution (several times better than Chandra and 50 times better than the Constellation-X resolution goal). Such a high energy observatory will be capable of detecting the earliest black holes and galaxies in the Universe, and will also study the chemical evolution of the Universe and extremes of density, gravity, magnetic fields, and kinetic energy which cannot be created in laboratories. A direct signature of the formation of the first galaxies, stars and black holes is predicted to be X-ray emission at characteristic X-ray temperatures of 0.1-1 keV from the collapsing proto-galaxies before they cool and form the first stars.

**Keywords:** X-ray, Missions, Generation-X, X-ray Astrophysics

## 1. SCIENCE MISSION AND OVERVIEW

**Generation-X (Gen-X)** will be an extraordinarily powerful X-ray observatory for all of astrophysics. It is intended as a high spatial resolution, high spectral resolution X-ray observatory with 1,000 times the sensitivity of *Chandra*. The requirements for **Gen-X** are science driven, based upon the goal of solving fundamental questions in astrophysics.

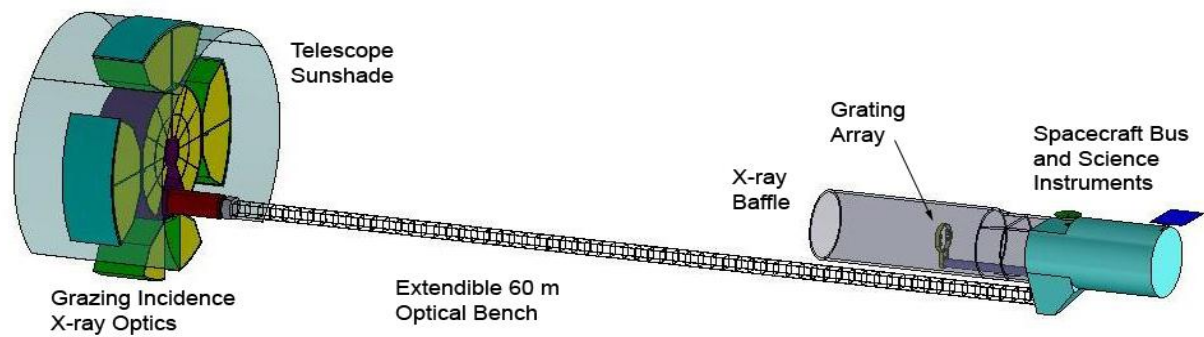
**Gen-X** was initially developed as a Vision Mission (VM: 2005-2006) study intended to lead to a mission start in the decade after next. It is currently being developed as an Astrophysics Strategic Mission Concept Study (ASMCS). This study takes advantage of the Ares V launch capability to develop a more efficient and cost effective single-launch, single spacecraft design (Figure 1) that significantly improves on the multiple spacecraft or formation flying mission designs developed for the VM study. Development of the scalable, high-resolution **Gen-X** optics technology will not only enable the **Gen-X** science, but also open the future to a full range of high-resolution X-ray telescopes and astrophysics goals.

Table 1: <i>Gen-X</i> Mission Parameters	
Effective Area (1 keV)	50 m <sup>2</sup>
Angular Resolution (HPD)	0.1 arcsec
Field of view (radius)	5 arcmin
Spectral Resolving Power	1,000-10,000
Background (0.1-2 keV)	0.004 ct ksec <sup>-1</sup> arcsec <sup>-2</sup>
Energy band	0.1 – 10 keV
Launch Vehicle and Orbit	Ares V to L2
Launch Date	2025-2030

A major new frontier in astrophysics is the study of the very first stars, galaxies, and black holes (BHs) from the initial, violent era at an epoch when the Universe was only a few percent of its present age (redshift,  $z$ , 10-20)[1], when the first massive stars exploded and their fragments collapsed into BHs. X-ray observations are a key factor in achieving this goal: these first black holes are expected to be powerful sources of X-rays which penetrate both the haze of the high- $z$  intergalactic medium (IGM), and the dust and gas expected around high- $z$  objects.

The **Gen-X** parameters needed to accomplish these scientific

goals are summarized in Table 1. To reach the faint,  $3 \times 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2}$  (0.1-10 keV), distant sources targeted for *Gen-X* we require exceptionally sharp images nearly an order of magnitude sharper than *Chandra*, the highest resolution X-ray telescope to date. We will achieve this major advance using nano-positioning actuators to adjust the mirror shape on-orbit. In this way we dramatically reduce background, as well as confusion with the multitudes of other foreground galaxies[2]. To collect enough photons *Gen-X* needs a mirror 15 times bigger than NASA's next major X-ray observatory, *Constellation-X* (*Con-X*), and several times larger than the proposed European *XEUS* mission. Those missions have angular resolutions of 15" (5" goal) and 5" (2" goal) respectively. A 5' field of view surveys sources efficiently.



**Figure 1.** The *Gen-X* configuration is enabled by the Ares V launch capability.

## 2. SCIENCE OBJECTIVES AND SIGNIFICANCE

X-ray emission generally arises from the existence of high temperature plasma or relativistic electrons. Hence, X-rays typically form in the most extreme conditions in the universe. Often, X-rays are the final energetic expression of material falling into a black hole and are produced in copious amounts in gamma-ray bursts and supernovae. Astronomical studies at X-ray wavelengths have intrinsic advantages over ground-based wavelengths. The most important of these may be the ability of X-rays to cut through the absorption of the intergalactic medium at large redshifts to see the first stars and galaxies as well as tracing the intervening absorption. **Using these special attributes *Gen-X* addresses the following key goals:**

1. Observe the birth of the first galaxies, stars and black holes.
2. Trace the evolution of structure, black holes, galaxies and the elements they produce, from the earliest times to the present epoch.
3. Probe the behavior of matter in extreme environments.
4. Address a wide range of other science.

Table 2 lists the basic *Gen-X* capabilities, and compares them with other X-ray missions.

Table 2: Mission Capabilities: log flux (cgs)			
Faintest:	Chandra	Con-X	Gen-X
Source Detection <sup>a</sup>	-16.5	-16.0 <sup>d</sup>	-19.5
Mod. Resolution Spectra <sup>b</sup>	-14.2	-15.5	-17.2
High Resolution Spectra <sup>c</sup>			
- Calorimeter	—	-13.5	-15.2
- Grating	-11.2	-12.5	-14.2

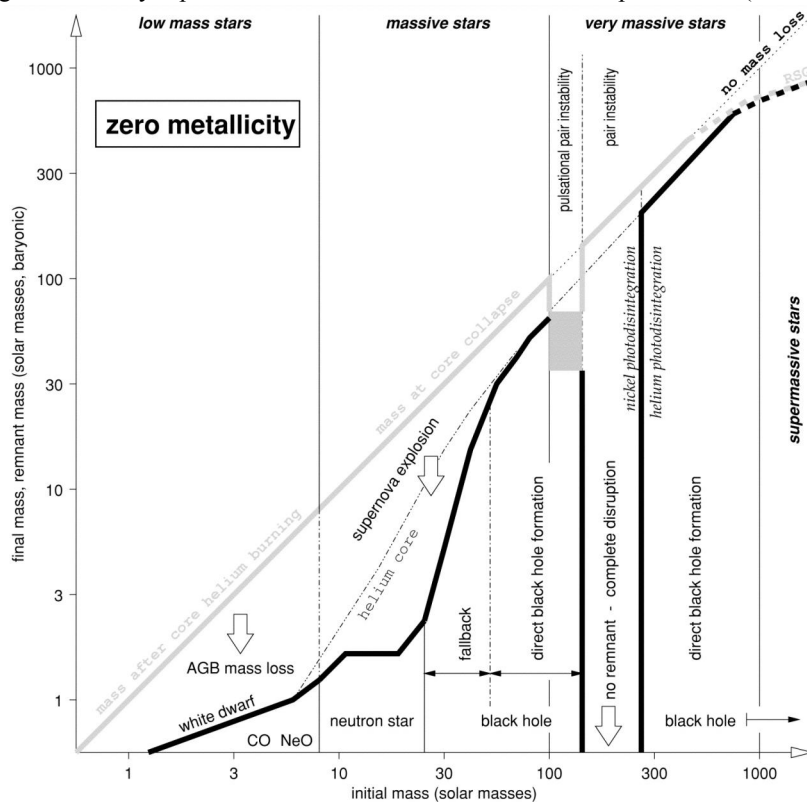
<sup>a</sup> 5 counts, <sup>b</sup> 10<sup>3</sup> counts, <sup>c</sup> 10<sup>5</sup> counts, all in 10<sup>6</sup> s (0.5-2keV); <sup>d</sup> in a 10<sup>5</sup> s exposure.

## 2.1 Observe the first Black Holes, Stars and Galaxies

At the opening of the 21<sup>st</sup> century, cosmology has been transformed and a radical new consensus has formed about how the Universe reached its present state starting from the Big Bang 13.7 billion years (Gyr) ago. We now believe that the normal matter, from which stars, planets and ourselves are made (“baryonic matter”), makes up only a few percent of the total mass/energy budget of the Universe. A far larger contribution comes from “dark matter”, as we have known for some time, and this is cold dark matter (CDM) as it is bound by gravity and not observable with any part of the electromagnetic spectrum. It has only just been realized that the great majority (70%) of the Universe is made up of something else that we see only through its effect in accelerating the expansion of the Universe. This acceleration – which was predicted by Einstein, who later repudiated the suggestion calling it “my greatest blunder”—acts like “anti-gravity” and is called “dark energy”. Starting with this new “Concordance Cosmology” ( $\Lambda$ CDM), highly successful numerical models of galaxy formation, assume that dark matter collapses under the force of its own gravity, dragging gas in with it. The gas heats to the virial temperature of the CDM halo and then cools and forms stars. Today the virial temperature of all galaxies of the mass of our galaxy and larger is greater than 3 million degrees i.e., the gas is heated to X-ray temperatures. In a sense, this is an X-ray Universe.

### 2.1.1 The first black holes

Theories of star formation in the early Universe require that the first generation of stars produce massive stars and large numbers of black holes. Black holes are expected to form from stars with masses greater than  $260 M_{\odot}$ . The initial masses of such black holes will be more than half the progenitor star (Figure 2)[3] and so at  $z=15$  we expect the formation of a population of black holes with masses of order  $100 M_{\odot}$ . Theoretical calculations [4] are rather unclear on the relationship of the supermassive black hole (SMBH) to the galaxy at early times since most galaxies at  $z=0$  have undergone many mergers and, presumably, their central SMBHs have either merged or been ejected. It is not known if most high  $z$  galaxies have SMBHs. These first black holes will begin to accrete matter and grow, as the over-densities in which they formed merge with neighboring over-densities. The maximum rate at which a black hole can grow is governed by the Eddington limit,  $L = 5.4 \times 10^{40} \text{ erg s}^{-1}$  for  $M = 500 M_{\odot}$ . Regardless of mass, the doubling time for a black hole accreting at the Eddington rate is the “Salpeter time” =  $4.5 \times 10^7 \text{ yr}$  (times an efficiency factor  $\epsilon/[0.1(1-\epsilon)]$ ). This growth is very rapid: from  $z=15$  to  $z=10$  there are four Salpeter times (0.2 Gyr), so a minimum mass ( $260 M_{\odot}$ ) black hole



will already have grown to  $8000 M_{\odot}$ , and will radiate at  $10^{41} \text{ erg s}^{-1}$ . Recent results on the faint *Chandra* sources [5] indicate that accretion occurs over much longer timescales than previously thought, suggesting that black hole masses are growing by factors of a few even since  $z \sim 1$ .

**Figure 2:** Initial-final mass function of non-rotating primordial stars ( $Z = 0$ ). The x-axis gives the initial stellar mass. The y-axis gives both the final mass of the collapsed remnant (thick black curve) and the mass of the star when the event begins that produces that remnant (e.g., mass loss in stars, supernova explosion for those stars that make a neutron star, etc.; thick gray curve). As the mass increases, the pulsations become violent, ejecting any remaining hydrogen envelope and an increasing fraction of the helium core itself. Above  $260 M_{\odot}$  the pair instability in non-rotating stars results in complete collapse to a black hole. (Adopted from [3]).

### 2.1.2 The First Galaxies and Stars

The Hubble Space Telescope/Great

Observatories Origins Deep Survey (HST/GOODS) survey has shown that big massive galaxies were considerably rarer at  $z > 3$  than at present. This agrees with expectation for  $\Lambda$ CDM Universe that small things formed first and later merged into larger objects. However, we have as yet no detailed information on the properties of most SMBHs at high redshifts, nor how they are related to their host galaxies (see [6] for the first estimates at  $z \sim 3$ ).

Other than X-rays, light from  $z \sim 15$ , where this first star formation occurs, can only be detected at wavelengths greater than  $2 \mu\text{m}$ , as absorption by the neutral intergalactic medium (IGM) removes all optical and UV photons out to wavelengths of  $0.12(1+z) \mu\text{m}$ . Only X-rays – with *Gen-X* – and the mid-IR – with James Webb Space Telescope (JWST) – provide direct views of this epoch.

A direct signature of the first galaxy formation should be X-ray emission at characteristic X-ray temperatures of 0.1-1 keV from the collapsing proto-galaxies before they cool and form the first stars. The exact details are still uncertain and will depend on mass scale and redshift. At a fixed mass-scale, the temperature scales as  $1+z$ , which acts to offset the declining mass of collapsing objects with redshift [7]. Young stellar populations produce copious X-rays. Given the scaling between star formation and X-ray luminosity ( $L_x = 10^{41} \text{ erg s}^{-1}$  per  $100 M_\odot$  per year of star formation) similar X-ray luminosities are produced on similar timescales by both proto-galaxy collapse and the first generation of rapid star formation, but star formation also produces heavy elements – “metals” (atomic number  $Z > 2$ ;) which are a necessary part of the planet building process. Luminosities of  $\sim 10^{41} \text{ erg sec}^{-1}$  are likely at  $z \sim 3$  to 10, producing an effective X-ray flux of  $10^{-18} \text{ erg cm}^{-2} \text{ sec}^{-1}$  at  $z \sim 3$ , the peak redshift of galaxy formation. This faint flux is two orders of magnitude beyond the capability of *Chandra* or other planned X-ray missions to reach.

With *Gen-X* sensitivity, it will be possible to distinguish between collapse and star formation for the origin of the highest redshift X-ray emission through both spatial differentiation and by the presence of metal emission lines characteristic of star formation. Since a resolution of  $0.1''$  corresponds to physical scales of 0.8, 0.6 and 0.3 kpc at  $z \sim 3, 6$  and 15 respectively, *Gen-X* will enable differentiation of the diffuse and compact components of the structures. Spectral emission lines will be redshifted into the very soft X-ray band and simulations demonstrate that *Gen-X* will be able to determine redshift, temperatures and metallicities of the primordial galaxies in regions of moderately low galactic column densities,  $< 2 \times 10^{20} \text{ atoms cm}^{-2}$ . Even for objects of  $kT \sim 0.5 \text{ keV}$  at  $z \sim 6$ , a detector resolution  $< 4 \text{ eV}$  will allow the detection of the strong Fe L shell lines, as well as the He-like lines of Mg and Si. The Si lines at a rest frame energy of 1.84 keV are visible at  $E \sim 0.26 \text{ keV}$  for a  $z \sim 6$  object. This means that *Gen-X* will emphasize the soft 0.1 to 2 keV X-ray band, analogous to the decision made for JWST to emphasize the IR band.

## 2.2 The Evolution of Black Holes, Galaxies and the Elements

There has been tremendous progress in observational cosmology over the past decade, especially in light of the recent results [1]. Tiny fluctuations from the mean density in the universe ( $\delta$ ) are amplified by gravity and gradually increase to clusters of galaxies with  $\delta \sim 1000$ , and galaxies with far larger overdensities.

### 2.2.1 Evolution of Black Holes

The seed black hole population created by the first stars grows by accretion, initially at the Salpeter rate (see §2.1.2), and by mergers spurred by the mergers of their host proto-galaxies. At later times global energetic arguments show that most black hole growth is due to accretion during “active” phases, during which they appear prominently as active galactic nuclei (AGNs) and quasars. Yet this growth is regulated so as to create the observed constant black hole to galaxy bulge mass ratio seen today.

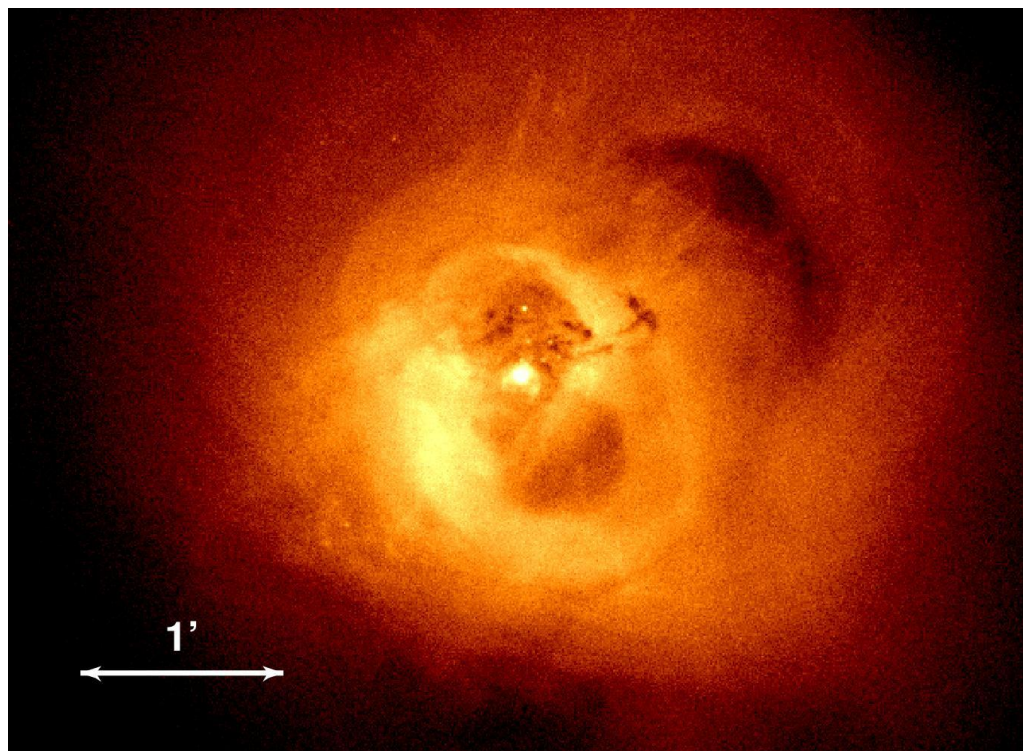
Explaining this “co-evolution” of galaxies and black holes requires that many of the merging dark matter halos contain black holes (at least above a critical initial fluctuation amplitude) so that galaxy mergers will lead first to binary black holes and later to black hole mergers, emitting gravitational radiation in the final seconds of their “death spiral”. So far a handful of “double black holes” have been detected as pairs of AGNs. One problem is obscuration. AGNs are often found in the dusty environments, both their own “obscuring torus” and the surrounding starbursts common in mergers. This obscuration cuts out light from the UV to the mid-IR in AGNs. Hard X-ray surveys ( $E > 2 \text{ keV}$ , in the emitted frame) find these AGNs.

The other limitation is inadequate angular resolution. *Chandra*, with  $\sim 1 \text{ arcsec}$  resolution, could only find pairs of AGN in the nearby Universe ( $1 \text{ arcsec} = 1 \text{ kpc}$  at  $z = 0.05$ ). *Gen-X* extends this to all redshifts as, in the Concordance Cosmology, 1 kpc is *never* less than  $0.1 \text{ arcsec}$ , making this resolution a critical parameter for *Gen-X*. Thousands of merger pairs will be available to *Gen-X*, complementing *LISA*’s ability to catch BHs in the act of merging, and finding many more such systems due to the longer timescales involved. By detecting pairs of accreting black holes *Gen-X* will

constrain the black hole “merger tree” [4] how many galaxy mergers contain two (or more) black holes, how many one, and how many none. This will illuminate the initial conditions for forming an initial seed black hole, as well as the processes governing black hole merging (the “rocket” and “slingshot” effects). The galaxy pair fraction is predicted to be magnitude (mass) and slightly redshift dependent. In a typical environment there would be of order 2000 mergers per square degree ( $I_{AB} < \sim 25$ ) for  $0.7 < z < 0.8$ , while in denser filaments these numbers rise by at least factors of 10. A 10' diameter field of view will thus include  $\sim 40$ -400 merger pairs, perhaps including higher order systems, and significant numbers of AGNs should be seen in mergers.

### 2.2.2 X-ray Evolution of Galaxies

*Gen-X* will explore galaxies from high  $z$  to the present, studying the X-ray evolution of their components with  $z$ . Most nearby galaxies in the 1-10 keV X-ray band are dominated by the non-nuclear X-ray emission from compact –neutron



**Figure 3:** A 53-hour Chandra ACIS observation of the Perseus cluster showing the impact of repeated nuclear outbursts on the gaseous content of clusters. Analysis of the data has revealed wavelike features that appear to be sound waves.

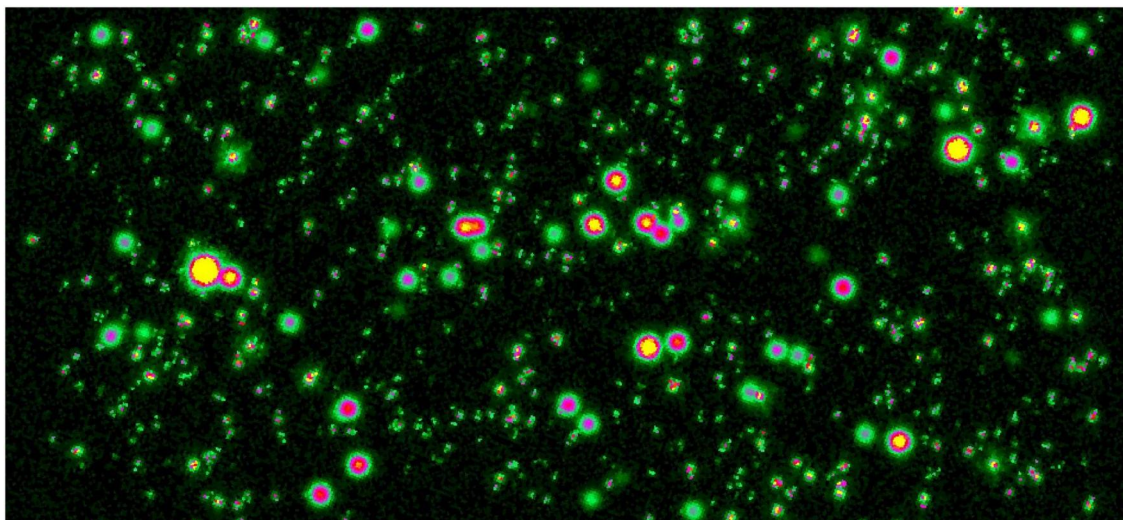
star or black hole - X-ray binaries in close orbits (Fabbiano 1989). Contributions from hot gas, super-winds and supernova remnants (up  $\sim 25\%$ ) increase in importance at lower energies. The integrated X-ray luminosity of individual galaxies ranges from  $10^{39}$  to  $10^{41}$  erg  $s^{-1}$ , and is well correlated with the infrared and optical luminosity [9,10,11,12]. The star formation rate (SFR) has undergone a strong cosmological evolution and is 10 times longer at  $z$  of 1, and 100 times higher at  $z \sim 3.5$ , than today [13]. An evolving SFR should increase the X-ray binary populations of galaxies and their overall X-ray luminosity [14]. Detailed observations of star forming galaxies at  $z < 0.3$  show that both the soft and hard X-ray luminosities do linearly track the SFR.

This is confirmed crudely by the *Chandra* “stacking” detection of the integrated emission of large samples of “Lyman break” galaxies ( $z=2-3$ ) [15,16], which reveals higher X-ray luminosities at higher  $z$ . By “stacking” sub-images centered on the positions of similar galaxies in comparable redshift ranges the detection threshold of *Chandra* can be lowered to  $\sim 10^{-18}$  erg  $cm^{-2}$   $s^{-1}$  – giving a “poor man’s” preview of what *Gen-X* will accomplish. These studies show that Lyman Break galaxies at  $z \sim 3$  [15] have an average luminosity of  $3 \times 10^{41}$  erg  $s^{-1}$ , while at  $z \sim 1$ , Balmer Break galaxies have a lower average luminosity of  $7 \times 10^{40}$  erg  $s^{-1}$  2002, (Nandra et al., 2002, Figure 1-9). This factor 5 increase in the X-ray luminosity from redshift 1 to 3 is consistent with an increasing star formation rate.

There are predictable and observable consequences of the increased SFR at high redshift for the X-ray detection of galaxies [17]. The peak-M [13] and Gaussian [18] SFR models, represent two extremes, and both predict that the

average X-ray luminosity of galaxies increases with cosmic time. Depending on the SFR model used, the average X-ray luminosity of galaxies in the Hubble Deep Field - North can be an order of magnitude higher than in the local universe. These rapidly star-forming galaxies produce a significant fraction of all the metals in the universe and *Gen-X* measurements, combined with JWST and Atacama Large Millimeter Array (ALMA), of their metal production rate, galactic winds and time evolution will provide the best measurements of the cosmic evolution of chemical abundances and star formation rate. Deep *Gen-X* observations will provide an alternate estimate of the cosmic SFR free of the effects of dust obscuration, provide a model-independent estimate of the evolutionary time scale of X-ray binaries (XRBs), as well as measure the metal production rate in the Universe as function of time.

In a  $10^6$  s Deep Field *Gen-X* will detect and study hundreds of galaxies, obtaining  $\sim 400$  counts for a  $z=3$  galaxy allowing the determination of line of sight absorption, spectral properties and fluxes to 20% accuracy (Figure 1-10). *Gen-X* will separate spatially the integrated XRB emission from a nuclear BH, and separate spectrally the hard XRB emission from hot gas [12], revealing the true SFR, even in dust enshrouded protogalaxies.



**Figure 4:** Slice of a simulated  $10^6$  s *Gen-X* image of the Hubble Deep Field produces a rich haul. *Chandra* saw 17 sources in the same exposure time [19]. With realistic fluxes and sizes most of the 3000 Hubble discovered galaxies are detected and over 800 have  $>400$  counts. This will allow the determination of their bulk spectral properties

The depths of the young Universe remain an almost purely theoretical frontier. Since we detect  $10^8 - 10^9 (M_{\odot})$  black holes (BHs) in quasars at  $z > 6$  (age  $< 1$  Gyr)<sup>3</sup>, the first stars, galaxies, and BHs must have been created earlier, and BH growth by accretion of matter must have been rapid, releasing X-rays in the process.

WMAP results [1] place this first epoch of energy injection into the Universe at  $z=10-20$  (age  $= 0.5-0.2$  Gyr). Stars of the first generation were likely to have been massive ( $> 100 M_{\odot}$ ), quickly burning their nuclear fuel. Stars smaller than  $260 M_{\odot}$  are expected to completely disrupt in powerful “pair instability” supernovae (SNe) [3], while more massive stars exploded and collapsed to form the first BHs.

Early BHs [19] of  $\sim 1000 M_{\odot}$  at  $z \sim 15$  can be detected at their Eddington luminosity by *Gen-X* at a flux of  $3 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1}$  (0.1-10 keV), 1000 times fainter than *Chandra* can reach. Most of the high-energy radiation from quasars is emitted at less than 100 keV which, at  $z \sim 15$ , will be observed below 7 keV, within the 0.1-10 keV *Gen-X* band. The 1.5 keV radiation, which can escape through the enshrouding dust and gas expected in these primordial objects, will be redshifted to  $\sim 0.1$  keV. *Gen-X* can thus detect *all active BHs* and measure the accretion luminosity of the high- $z$  Universe. Redshifts can be estimated photometrically from broad-band infrared detection of the Lyman- $\alpha$  break. The early SNe may be visible as Gamma-ray bursts (GRBs; [20]) detectable by other satellites flying contemporaneously with *Gen-X*. *Gen-X* can then obtain spectra of their X-ray afterglows, determining GRB distances and total energy output, and probing the high- $z$  intergalactic medium (IGM).

Black hole masses are strongly correlated to the bulge mass of the galaxy containing them[22]. Both black holes and galaxies experienced a rapid era of growth over  $2 < z < 4$ . At this age galaxies will have several young SN remnants (SNR) and “ultraluminous X-ray sources” (ULXs) [23,24], and also intermediate mass BHs (several  $1000 M_{\text{sol}}$ ) which may result from slow accretion onto smaller BHs or be formed in place by an unknown mechanism. *Gen-X* can detect these at the expected fluxes of  $> 10^{-19} \text{ erg cm}^{-2} \text{ s}^{-1}$  (0.1-10 keV). *Hubble* shows that at such redshifts galaxies are  $\sim 0.5''$  across, requiring the low background rate specified in Table 1 for detection. Separating SNRs, ULXs, and low luminosity AGN (supermassive black holes, SMBHs) against the unresolved X-ray binary (XRB) sources and the hot interstellar medium (ISM), requires an angular resolution  $\sim 0.1''$  in order to resolve 1 kpc anywhere in the universe. Efficient deep surveys and mapping of sources requires a field of view of order  $5'$ , which matches JWST.

### 2.2.3 Warm-Hot Intergalactic Medium

At redshift  $< 2$  the majority of the baryonic intergalactic matter is highly ionized with temperatures of  $T = 10^5 - 10^7 \text{ K}$ , and so eludes detection in the optical band. However, highly ionized metals in these so called Warm-Hot Intergalactic Medium (WHIM) filaments still produce significant opacity to soft X-ray photons, and therefore can be detected through metal absorption lines in the 0.1-2 keV spectra of background sources, provided the detector has sufficient spectral resolution to resolve the lines and there are enough counts per resolution element in the continuum adjacent the line, to contrast the absorption.

The first two WHIM filaments have been recently detected using *Chandra* grating spectra, thanks to a “target of opportunity” of a blazar in outburst, when it was some 2 orders of magnitude brighter than the otherwise brightest quiescent AGNs in the X-ray sky [25]. While the results agree with predictions, this is only a rough test with a factor of several uncertainty. Also, the lines are unresolved, so the derived column densities – and hence masses – depend on the assumed Doppler “b” parameter. It is hard to go any further without additional capabilities. No other extragalactic source is available for this kind of study, and similar signal-to-noise X-ray spectra can only be obtained with  $> 10 \text{ Msec}$  *Chandra* or XMM-Newton integrations. Current instrumentation falls short of this task.

More detailed studies of the WHIM are important, since they will allow us to: (a) find the “Missing Baryons” and so verify theories of structure formation; (b) study the Ecology of the Universe via abundances; (c) discriminate between mechanisms for IGM-galaxy and AGN-galaxy feedback; (d) reconstruct the heating history of the Universe; (e) build maps of the Dark Matter to compare with baryonic matter fluctuations at redshifts up to 2 and on large length-scales of  $10$ 's of Mpc.

To achieve these goals requires high spectral resolution,  $R > 5000$ :

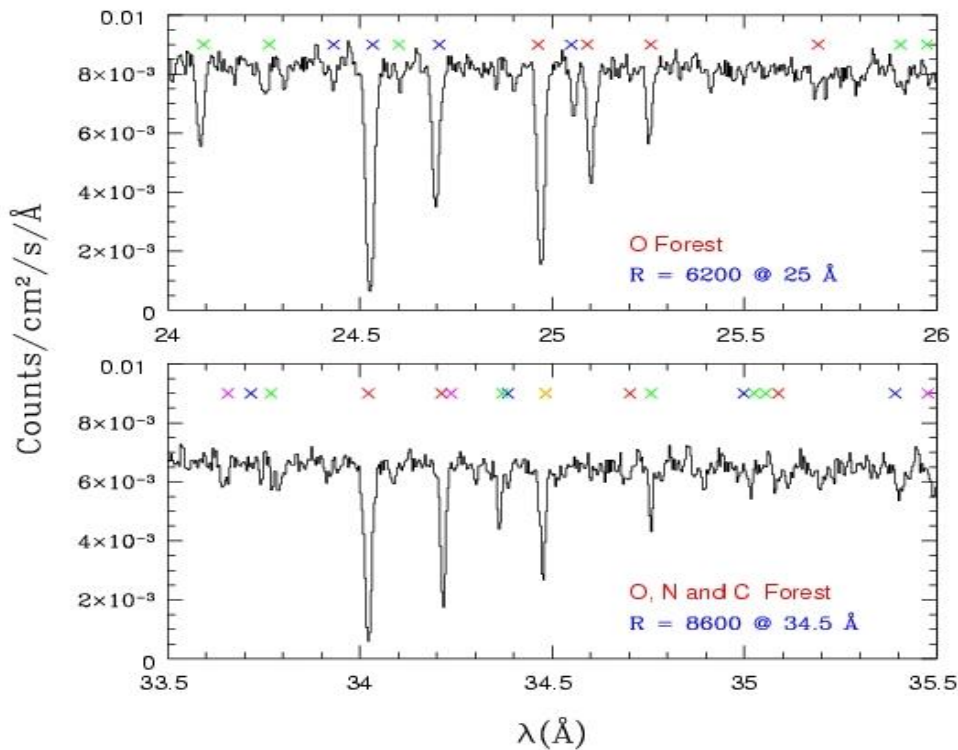
- Metal absorption lines due to the WHIM are expected to have total (i.e., thermal plus micro-turbulence) Doppler parameters of about  $50\text{-}150 \text{ km s}^{-1}$ . These will be fully resolved at a resolution  $R > 5000$ . Resolving the lines will allow us to break the degeneracy between Doppler parameter,  $b$ , and ion column density, and so measure both.
- The detection of multiple absorption lines from different ions of the same metals, and from different metals will enable a model-independent estimate of the ionization state of the gas, and so a measure of the relative metallicity of the systems. These give the cosmological mass density  $\Omega_b^{\text{WHIM}}$  of the WHIM filaments (as a function of the absolute metallicity).
- Metallicity patterns will discriminate between different mechanisms for the IGM-galaxy and IGM-AGN feedback process.
- Different WHIM phases are predicted at scale-lengths of 0.1-1 Mpc and can also be resolved at  $R > 5000$  in at least half of the detected systems (the centroid of  $> 10\sigma$  absorption lines will be determined at better than  $\sim 0.4 \text{ m \AA}^{-1}$ , i.e.,  $5 \text{ km s}^{-1}$  at 0.5 keV). This is vital to properly measure the ionization balance of the gas and so not to over-estimate  $\Omega_b^{\text{WHIM}}$ .

Even higher spectral resolution,  $R > 10000$  at 0.5 keV, would qualitatively increase the diagnostic capabilities of X-ray spectra, making them virtually model-independent. Such measurements:

- Will allow us to disentangle thermal and internal-turbulence motion (by comparing the widths of absorption lines from different metals) and so will provide a model-independent measure of the ion temperature of these systems.
- Discriminate between different ionization mechanisms (collisional ionization, hybrid collisional-ionization/photoionization, non-equilibrium ionization of low-density post-shocked gas, etc.)

With this understanding in hand we can constrain the H density of the absorber, enabling **absolute** metallicity determinations and so **absolute** measurements of  $\Omega_b$ . With baryonic matter distributions we measure cosmological parameters through WHIM filaments density fluctuations, at redshifts up to 2 and on large scale-lengths – 10s of Mpc.

To address these important astrophysical issues, thousands of WHIM systems along many of lines of sight need to be detected. *Gen-X* will enable this science. A thousand WHIM systems can be detected in a 1 Msec program probing 20 lines of sight in 50 ksec observations of  $z < 1$  quasars with  $F_{0.5-2 \text{ keV}} > 0.05 \text{ mCrab}$  ( $1 \text{ mCrab} = 2 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ ). Mostly H-like and He-like transitions from C, N, O, Mg, Si, S and Fe, will be detected. There are 115 such objects in the ROSAT all-sky Sky Survey (RASS).



**Figure 5:** A 50 ks *Gen-X* simulation of a 0.5-2 keV 0.05 mCrab QSOs at  $z=1$  ( $\Gamma=1.8$  and Galactic  $NH=1.5 \times 10^{20} \text{ cm}^{-2}$ ). The spectral simulation uses a resolution of  $\Delta\lambda = 4 \text{ mÅ}$  (i.e.,  $R=6200$  at  $25 \text{ Å}$  and  $R=8600$  at  $34.5 \text{ Å}$ , and a grating efficiency of 25%.

### 2.2.3 Chemical Evolution of the Universe

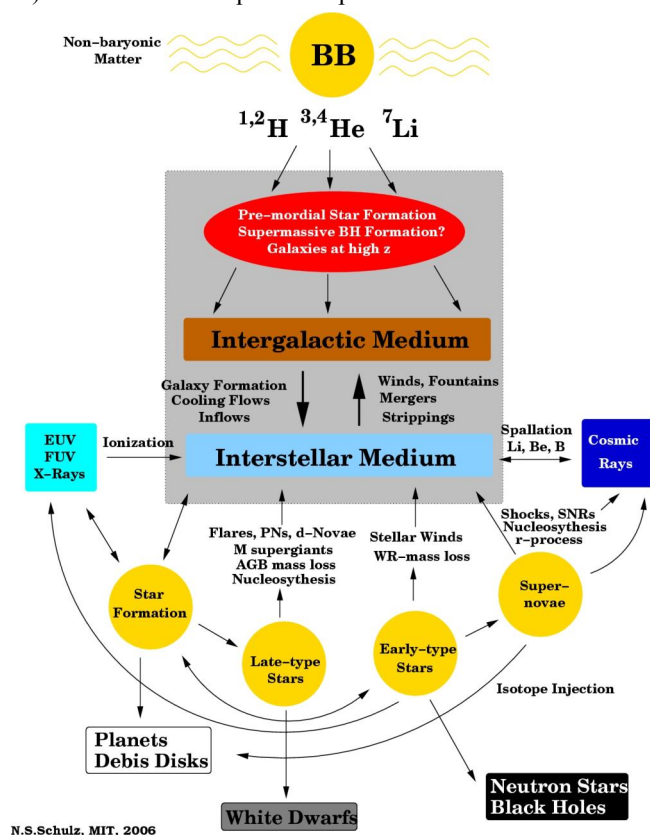
The processes that create the chemical elements out of hydrogen are known in some detail: the creation of the light elements (He, Li, D) in the Big Bang, and of the heavier elements in stellar interiors is mostly well documented. How those elements became distributed as we see them in the Universe is much less understood. Many processes seem to be at work: supernovae, stellar winds, outflows from quasars, and mergers of groups and clusters (Figure 6), all move around large amounts of material, and produce patterns of element distributions (abundances) that we can measure. Much of this motion occurs at high velocities, so that when the gas is halted by shocks, it heats up to X-ray temperatures. This puts diagnostics of abundances out of reach of optical or infrared telescopes in many of the most telling environments.

Fortunately, the X-ray band, particularly below 2 keV, is rich in atomic transitions of many elements. X-rays are particularly sensitive to K-shell absorption from high abundance elements like C, N, O, Ne, Mg, Si, S, Ar, Ca, Fe, and Ni as well as L-shell absorption of Fe. Since these elements are abundant in astrophysical contexts, they can be used to trace the chemical evolution of the Universe with cosmic time. Moreover, at high densities, resonance absorption and backscattering of X-ray transitions also arise from simple and complex molecules containing these elements, so that X-ray spectroscopy can probe cold gas too.

Whether in emission or absorption, the imaging and spectroscopic capabilities available on *Chandra* and *XMM-Newton* only reveal the tip of the iceberg and clearly fall short of efficiently reaching out into the necessary spatial and dynamic domains. *Con-X* will make considerable improvements and allow first serious surveys of hot matter in galactic halos and absorbers in the ISM and possibly the WHIM if it can deliver promises of resolving powers of  $\lambda/\Delta\lambda \sim 1500$  at 21 Å (0.6 keV). Note that most spectroscopic tracers for the Galactic halo gas as well as the gas phases of the ISM in the X-ray band, are to the long wavelength side of 13.4 Å (925 eV) with the majority longward of 19 Å. For galaxies at observed  $z > 0$  the band shifts in a corresponding manner. So low energy, wide area coverage and high spectral resolution are crucial.

*Chandra* and *Con-X* mark only the beginning of chemical evolution studies in X-rays. To perform proper and deep surveys that lead to analyses that support and significantly improve results we need the power of *Gen-X*. Where *Chandra* lacks the power and *Con-X* (in many aspects) resolution, to probe galaxy ISMs at redshifts up to 6, *Gen-X* provides the final punch.

Abundances span a wide range. For example, the high redshift IGM has only a few percent of solar abundances, yet high redshift ( $z > 4$ ), quasars seem to have super-solar abundances [26], far above that of their large-scale surroundings. Quasar winds may thus be important in the chemical enrichment of the early IGM. *Gen-X*, using high resolution spectroscopy, will measure the quasar abundances more completely than possible in other wavebands, since much of the gas is highly ionized, and will also measure the enrichment of the IGM at high  $z$ , so covering both ends of this process.



**Figure 6:** Schematic diagram illustrating the chemical evolution of the Universe. Probing ISMs at observed redshifts of up to  $z \sim 6$ , as well as probing warm-hot phases in the IGM is a straightforward task for *Gen-X*.

### 2.3 Matter in Extreme Environments

By its very nature, X-ray emission gives us a direct view of processes connected with matter in extreme environments: extreme density, gravity, energy, and magnetic field. Table 3 gives examples for each case.

*Gen-X* provides a unique capability for approaching this extreme physics. It combines a large area that will provide a torrent of photons, with good angular resolution that will pick out individual sources in crowded fields such as globular clusters and external galaxies, and will reveal structures of shocks and jets with high spectral resolution to probe the dynamics of the accretion process.

Accretion is the fundamental process that drives XRBs and active galaxies. Yet accretion physics is not yet understood. Models incorporating magneto-rotational instabilities (MRI) are developing, but need observational constraints. *Gen-X* high-resolution spectra and timing measurements in the Milky Way and nearby galaxies will provide such tests. The same *Gen-X* properties complement the extremely high spatial

resolution of the X-ray *Black Hole Imager*, while both X-ray missions complement gravity wave experiments, such as *LISA*, because they probe static gravitational fields, while gravity-wave instruments are sensitive to dynamic processes such as BH mergers.

<b>Table 3. Extreme Conditions of Matter</b>
<b>3.1 Extremes of Density: Neutron Star (NS), Quark and Hyperon Condensates</b>
<i>Gen-X</i> will give accurate gravitational redshifts and temperatures of isolated or quiescent NS surfaces, determine the mass/radius relation [27], strongly constraining the equation of state [28], and probe forms of ultra-dense matter.
<b>3.2 Extremes of Gravity: At the BH Event Horizon</b>
<i>Gen-X</i> will study rapid change of the Doppler and gravitational distortions in X-ray line profiles [29,30,31,32] on a dynamical crossing time, 30 times faster than <i>Con-X</i> , determining masses and spins for SMBHs as a function of <i>z</i> .
<b>3.3 Extremes of Magnetic Field that <i>Gen-X</i> will explore:</b>
(1) X-ray radiation from the surface of magnetars carries several spectral signatures of Quantum Electro-Dynamics [33, 34], which predicts that light is slowed by strong magnetic fields[35, 36].
(2) <i>Pulsar</i> winds changes from Poynting flux to particle dominated between light cylinder and termination shock.
<b>3.4 Extremes of Kinetic Energy: Relativistic Jets in AGN and micro-quasars</b>
<i>Gen-X</i> images of jets will measure knot speeds [37] and probe energy conversion through resolving the energy loss scale. Spectroscopy and wider field imaging will help to unravel how relativistic jets are launched.

## 2.4 Broad Spectrum of Science Objectives

*Gen-X* also addresses fundamental astrophysics goals across the whole gamut of celestial phenomena, from protostars and planets, to distant quasars. Table 4 provides specific examples.

<b>Table 4: Broad Science Capabilities</b>
Imaging and reverberation mapping of protoplanetary disks in fluorescent X-rays, protostellar flare effects on disk dynamics, chemistry and <i>planet formation</i> [38,39].
Spectra of other “Suns” elucidate: <i>Sun-Earth connection</i> over time and <i>radiation history of the habitable zone</i> [40].
One image will show the entire compact binary population of a globular cluster and determine <i>whether compact binaries halted core collapse</i> .
<i>Rapid filament motions</i> , now visible only in the Crab and Vela, can be mapped in ~50 pulsar-wind nebulae.
A 6-month survey of 20 deg <sup>2</sup> with <i>Gen-X</i> will yield a catalog with <i>the X-ray equivalent of the Sloan Digital Sky Survey</i> <sup>8</sup> , yielding millions of sources, with the accurate positions needed for follow-up in optical or other bands.

## 3. REQUIRED CAPABILITIES

Table 5 summarizes the baseline mission parameters, derived from the science objectives and required observations. These parameters were initially derived as part of our VM study VM study and remain valid in the current ASMCS activity. To collect 10 counts from a 1000 M<sub>⊙</sub> black hole at redshift 15, in 10<sup>6</sup> seconds, requires an effective area of 50 m<sup>2</sup>. Such a small number of counts still allows significant science. With the worst-case baseline detector background, we then require 0.1” resolution for 10 counts to be statistically significant against the 0.4 background count, and considering the number of spatial resolution elements. These two parameters fundamentally drive the mission, with system trade-offs that can be made among energy resolution, bandwidth, background, and exposure time, allowing consideration of the “study limit” column parameter.

## 4. STATUS

Generation-X was first approved as Space Science Vision Mission in 2006. Vision Missions were intended for the 2025 time frame. The final report of the vision mission program was presented to NASA in Spring 2007. This report concluded that all primary goals could be met with the baseline parameters given in Table 6. The vision mission report concluded that the optics would be the most difficult part of the development, requiring the longest lead up time. **Gen-X** was approved in February 2008 as an Astrophysics Strategic Mission Concept Study (ASMCS). This current study has four tasks: (1) To refine the science case, especially to create more realistic simulations (2) To refine the mission concept to use the ARES V (3) To expand the technology roadmap and (4) to develop a technology test bed for the optics.

Table 5: The Key Gen-X Science Drivers Trace to Mission Parameters								
Driven Parameter*:	AR	EA	E_disp	E_non-dsp	FOV	E_Min	E_Max	other
<b>Detect the First Galaxies, Stars and Black Holes</b>								
➤ The First Galaxies & Stars	0.1"	50m <sup>2</sup>	–	4eV	1'-2'	200eV	10keV	
➤ The First Black Holes	0.5"	50m <sup>2</sup>	–	4eV	1'-2'	100eV	10kev	
<b>Evolution of Structure, Black Holes, and Galaxies and the Production of Elements</b>								
➤ Evolution of Black Holes	0.1"	50m <sup>2</sup>	–	4eV	5'-10'	200eV	10keV	
➤ Evolution of galaxies to z=10	0.1"	50m <sup>2</sup>	–	4eV	1'-2'	300eV	2kev	
➤ Structure: WHIM	0.5"	25m <sup>2</sup>	R~8000-10,000	–	1'-2'	100eV	10kev	
➤ Chemical Evolution of the Universe	0.5"	50m <sup>2</sup>	5000@<1keV	4eV	1'-2'	300 eV	10 kev	Background < 0.004 cnts ks <sup>-1</sup> arcsec <sup>-2</sup>
<b>Probe the Behavior of Matter in Extreme Environments</b>								
➤ Extremes of Density: Neutron Stars	0.1"	50m <sup>2</sup>	3000	2eV	1'-2'	1 keV	10keV	Count Rate: >10 <sup>5</sup> cps Timing Res.: 50 μsec
➤ Extremes of Gravity: Black Holes	0.5"	50m <sup>2</sup>	1000	10eV	1'-2'	1 keV	10 keV	Count Rate: > 10 <sup>5</sup> cps, Timing Res.: ~50 μsec

\*Column Headings: Angular Resolution, Effective Area, Dispersive Energy Resolution, Non-dispersive Energy Resolution, Field Of View, Energy Range Minimum, Energy Range Maximum

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